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ANALYTIC BALLISTIC PERFORMANCE MODEL OF WHIPPLE SHIELDS

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ABSTRACT

The dual-wall Whipple shield is the shield of choice for lightweight, long-duration flight.

The shield uses an initial sacrificial wall to initiate fragmentation and melt an impacting threat that expands over a void before hitting a subsequent shield wall of a critical component. The key parameters to this type of shield are the rear wall and its mass which stops the debris, as well as the minimum pressure generated under threat particle impact of the sacrificial wall and the amount of void that is available for expansion. Ensuring the minimum pressure is sufficiently high to achieve large scale fragmentation/melt of the threat particle enables the expansion of the threat and reduces the momentum flux of the debris on the rear wall. Three key factors in the minimum pressure achieved are the thickness of the sacrificial wall relative to the characteristic dimension of the impacting particle, the density and material cohesion contrast of the sacrificial wall relative to the threat particle and the impact speed. The mass of the rear wall and the sacrificial wall are desirable to minimize for launch costs and dynamic concerns making it important to have an understanding of the effects of density contrast and impact speed. In this paper a fourth key parameter is identified related to fragmentation, which corresponds to the ratio of the size of the projectile relative to the transition from brittle to ductile hole growth in the projectile.

Ballistic limit equations have been developed to define the failure limits of a MMOD shield, generally in terms of projectile diameter (or mass), impact velocity, and angle. Within the

range of impact velocities relevant for Earth-orbiting spacecraft, three distinct regions of penetration phenomenology have been identified for Whipple shields:

- Low velocity: the projectile is eroded (and possibly deformed) during its passage through the bumper plate, but is not fragmented. Thus, perforation of the rear wall is by a fragment with a mass and speed equal to or less than the original impactor.
- Intermediate (shatter) velocity: impact velocities are sufficient to induce projectile fragmentation upon impact with the bumper plate, resulting in a coarse debris cloud with large solid fragments. Increasing velocity within the shatter regime results in increased fragmentation, and eventually melting, of the projectile and bumper fragments, generating a finer and more evenly dispersed debris cloud. Failure of the rear wall is a complicated combination of modes observed at low- and hypervelocity.
- Hypervelocity: the projectile and holed-out bumper material is completely, or nearly completely, melted and/or vaporized by the initial impact. The resultant debris cloud impacts over a dispersed area of the rear wall, loading it impulsively and inducing failure through rupture or petalling.

While each of these regimes are well observed with extensive empirical methods to describe these regions, differences in impactor materials, configurations of shields and questions about the limitations of the attainable impact speeds have left questions that are difficult to answer from completely empirical methods.

To develop a broader understanding of the performance of these shields to enhance extrapolation, an analytical effort to understand these regions has been undertaken that involves solving mass and momentum equations for a Lagrangian description of the projectile and the walls of the Whipple shield to yield a transmitted particle velocity of the material based on

whether or not the wall is optimum (shock wave reaches the rear of the threat particle before the rarefaction wave) or non-optimum (rarefaction wave decreases the strength of the shock wave reducing the amount of deceleration of the incoming threat). With respect to the sacrificial wall, once the average transmitted particle velocity is known an energy balance can be performed to determine the rate of the lateral release of the threat projectile and target material prior to the impact of the rear wall. The momentum flux of the impact debris is then used with the rear wall, and the threshold of the ballistic performance is achieved when the particle velocity is less than the rear wall is capable of supporting.

Aside from pure mass of the rear wall, one of the most critical aspects of Whipple shield design is understanding the expansion rate of the projectile and the sacrificial wall, which controls the three velocity regimes discussed. Recent scale experiments have shown that this is not necessarily tied to a fixed impact condition, but changes depending on the strain rate of the projectile. In the analytic model, a possible explanation for the transition from the low to intermediate velocity regime is the transition from brittle to ductile fracture, and a possible explanation for the transition from an intermediate to high velocity regime is due to a limit in lateral wave speeds that have been observed in experiments designed to measure them.

This paper reviews the previously developed empirical models and documents the derivation of this analytical model. It discusses the constitutive properties that are necessary to account for the Whipple shield performance in the analytic model. The developed empirical models and the analytic model are then compared to various tests of aluminum shields with various impacting materials including scaling tests to isolate strain rate behavior for both aluminum and steel projectiles, like that shown in Fig. 1, and a generalized database of over two thousand impact tests that has been compiled.

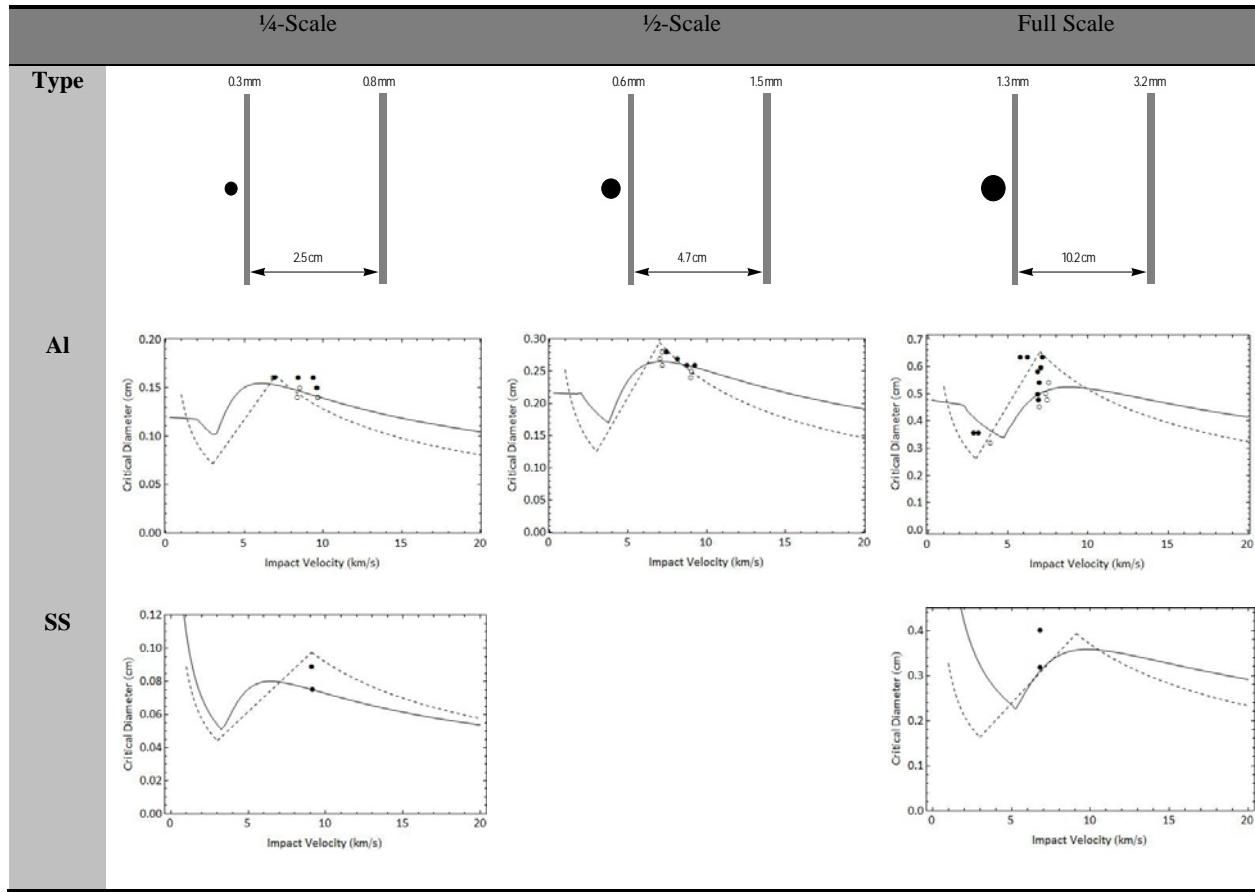


Figure 1 – Double wall shield performance for quarter, half and full ISS US lab module shields for Al2017 and SS440C projectiles impacting normal to the shield (open-shield intact, closed-shield failed) with the analytic ballistic performance model (solid line) and the latest double wall ballistic limit equation (dashed line).